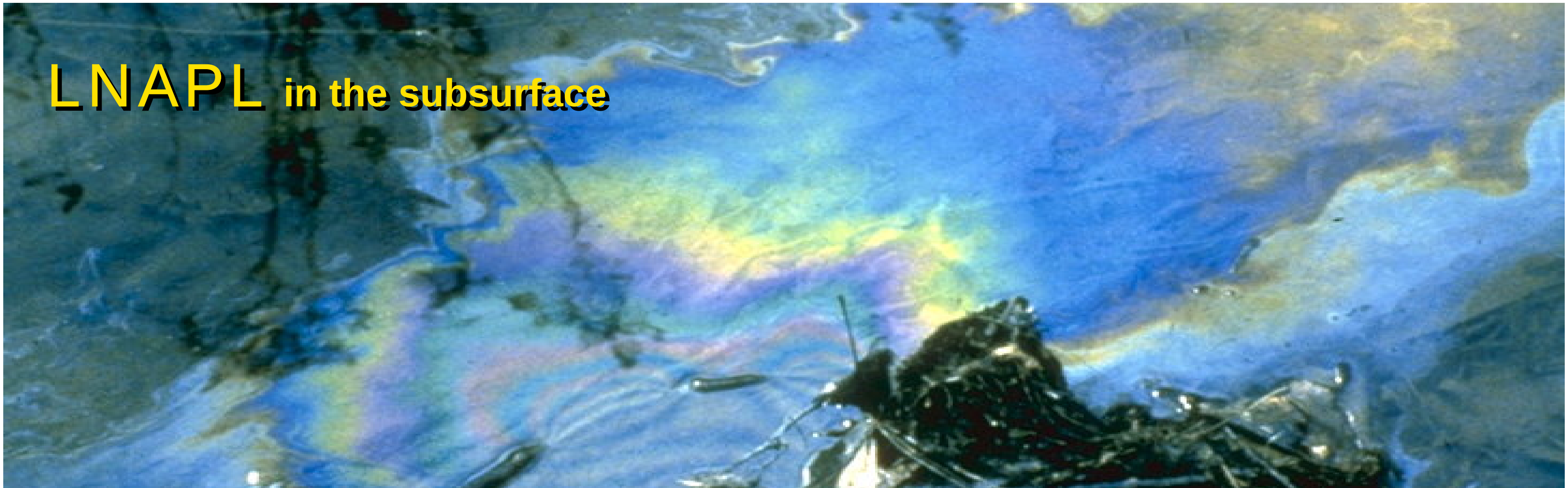

LNAPL in Fine Grained Soil – measured LNAPL saturations – and residual saturation

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&

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Common misconceptions about LNAPL

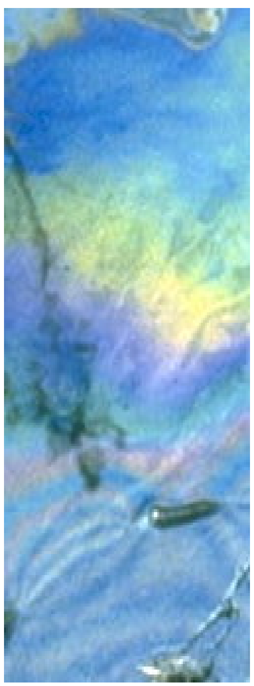
LNAPL floats on the water table

LNAPL does not penetrate below the water-table

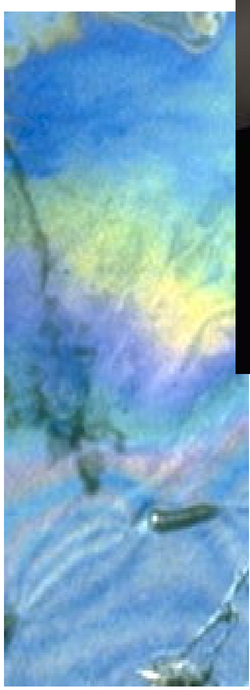
LNAPL thickness in a well fluctuates too much and is meaningless

LNAPL forms a pancake like lens of uniformly high saturation on the water table

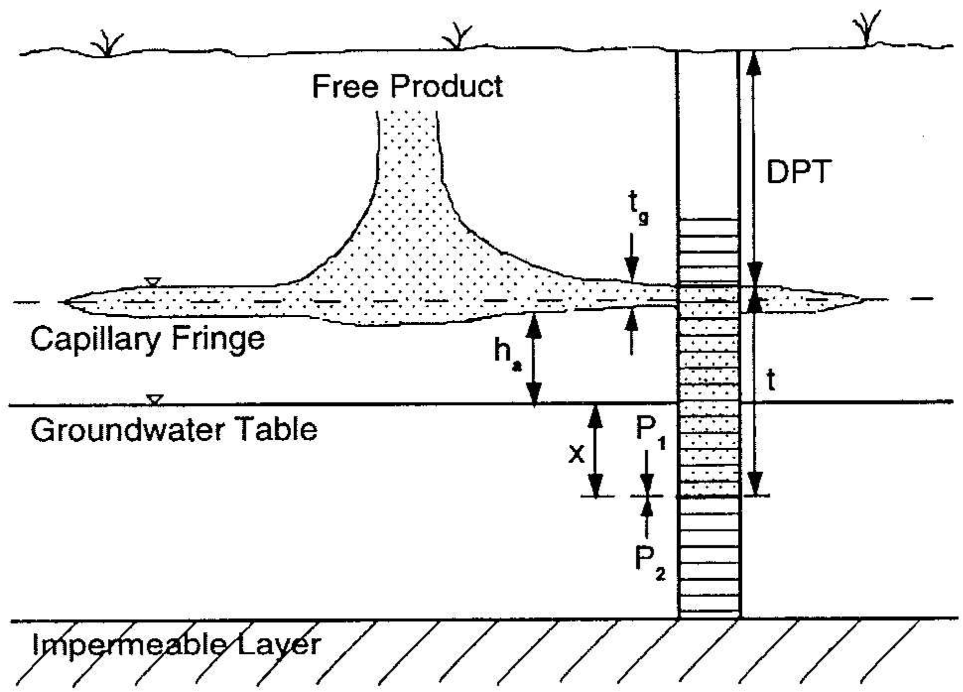
If you see LNAPL in a well it is mobile and migrating



That was the old way to think about LNAPL!

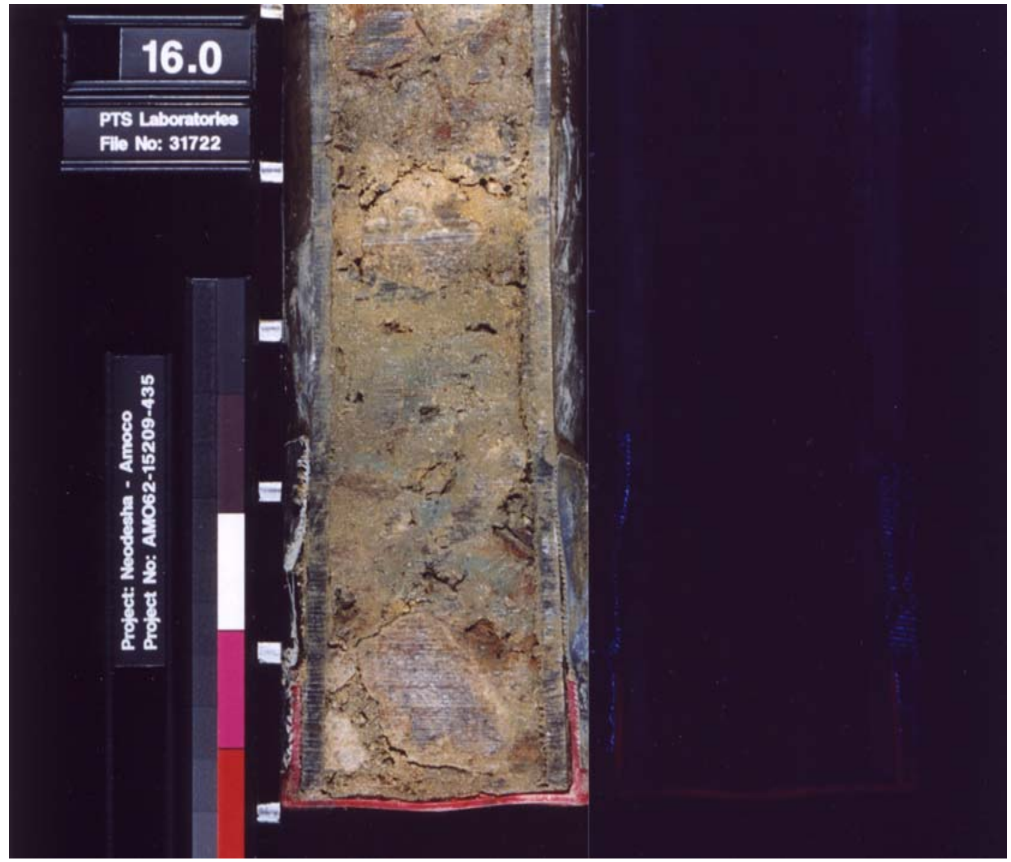


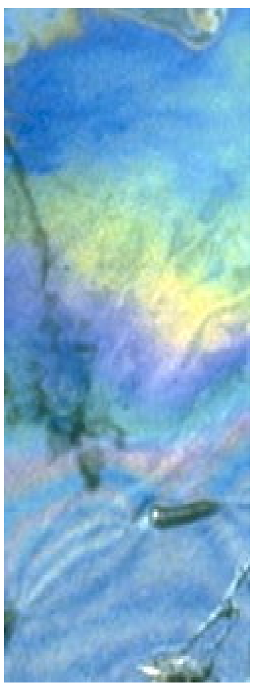
Works well for LNAPL spilled into sand in fish tanks

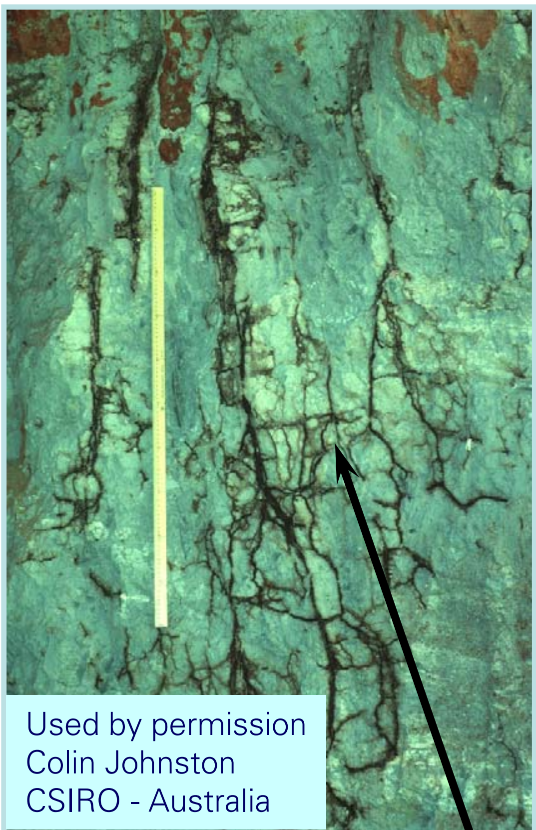


No longer focused on idealized porous media – now focused on real world soils

(SW-SC)





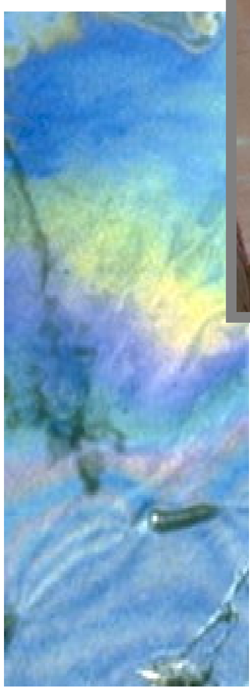


Used by permission
Colin Johnston
CSIRO - Australia

(CH or CL?)

Conceptual model for FGS

Real world soils (cont’d)



(CH)

(SC)

Basic concept – covered in basics

In most soils there are BIG pores and little pores

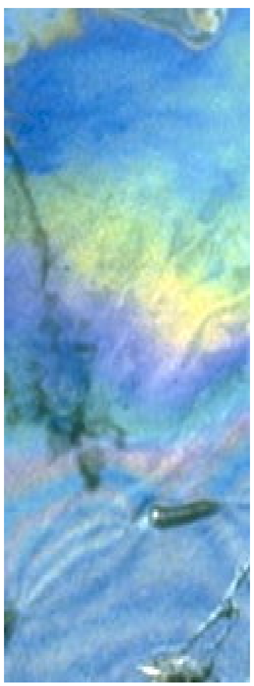
LNAPL likes the BIG pores (it can push the water out)

Water likes the little pores (LNAPL doesn't – can't get in)

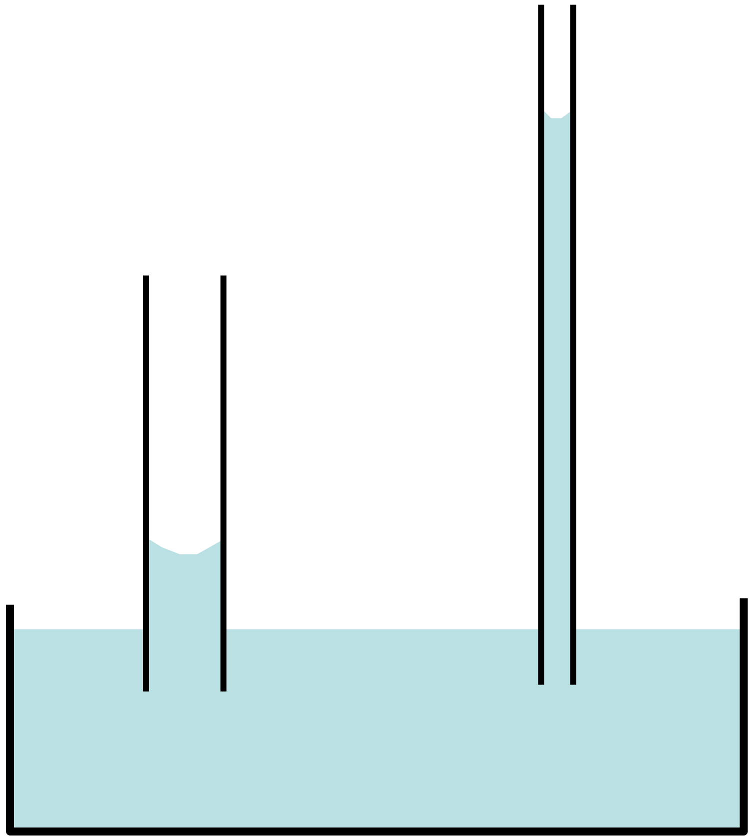
LNAPL is off to the races and happy in the big pores

LNAPL needs excess pressure to get into little pores

If there is not much LNAPL pressure it will stay in the big pores

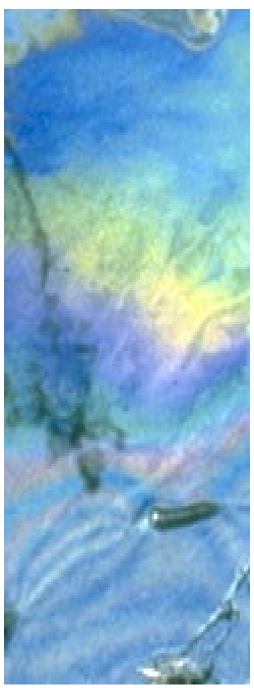


As pore size gets smaller - threshold entry head gets bigger



$$h_d = \frac{2\,\sigma \cos(\theta)}{r\,(\rho_w - \rho_n)\,g}$$

Basically says that water is held in smallest pores most tightly

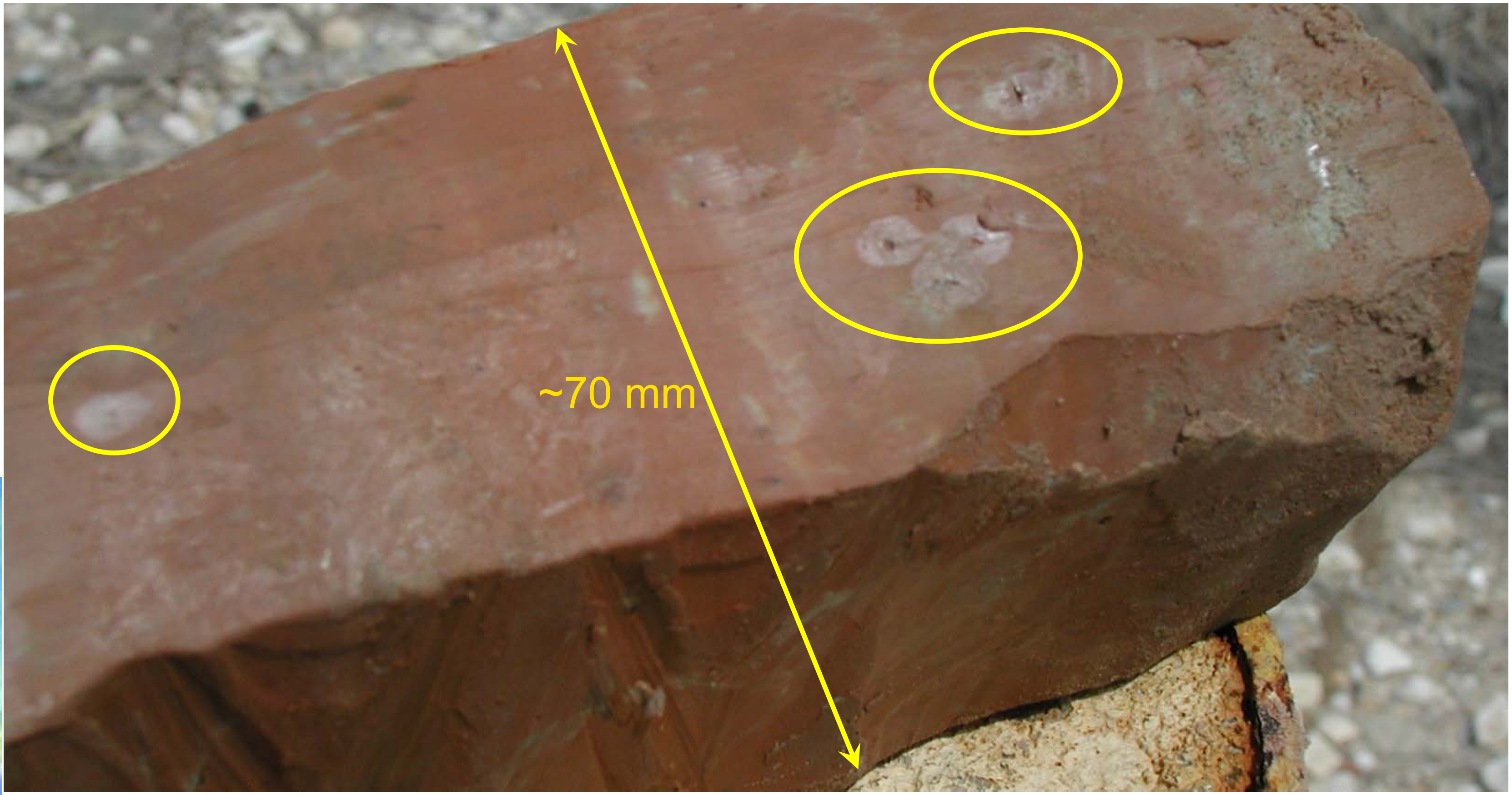


Hydrogeology and Structure of FGS

Macropores Exist in FGS

- Include: Desiccation cracks; fractures; dewatering features; etc
- Some are open, some may be filled with sand
- Can be effective down to 10 m (Simpkins and Bradbury, 1990)
- Macropores observed at most FGS sites

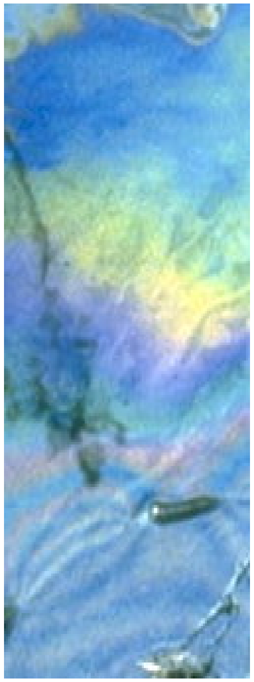
Example of Macropores



~ 10 ft (3 m) Below “water table”

Example of Macropores

Coarse Silt (ML) 3 m bgs (9 ft)



Rough example of importance of pore size and threshold entry head

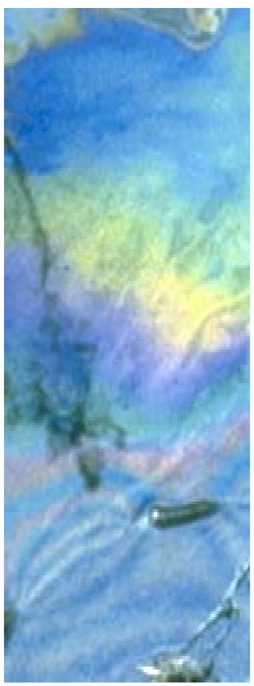
$$h_d = \frac{2\,\sigma\cos(\theta)}{r\,(\rho_w - \rho_n)\,g}$$

Capillary Suction / Rise:

- Height of capillary rise in FGS (Silty Clay CL):
  - ~ 20 ft (6.1 m) (calc.D10) with groundwater at 14 ft (4.3 m) bgs
- Height of capillary rise in 0.5 mm macropore
  - ~ 2 inches (5.6 cm)

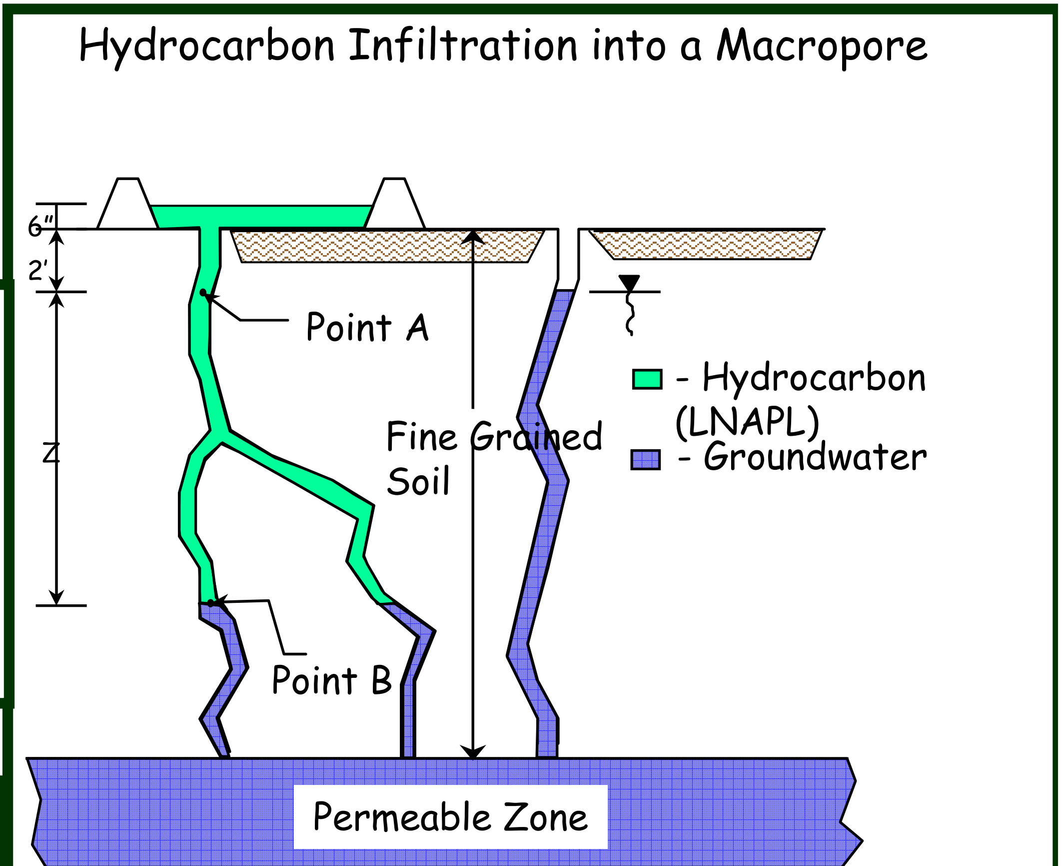
Threshold Entry Head:

- LNAPL threshold entry pressure into FGS (Silty Clay CL) sites soils:
  - D 10 = 5 ft (1.5m) of HC Head
  - 1/5 D 10 = 24 ft (7.3 m) of HC head
  - 0.5 mm macropore = 0.6 inch (1.5 cm) of HC head
  - McWhorter similar conclusions



How far below the water table can LNAPL go? (hydrostatic case)

Macropore Diameter = 0.5 mm
Hydrocarbon is Diesel:
Specific Gravity = 0.86
Interfacial Liquid Tension = 25 dyne/cm
Contact Angle = 40°
Surface Tension = 20 dyne/cm
Pool Height = 6 inches (15.2 cm)
Depth to water = 2 feet (0.61m)
Dyne = (cm•g)/sec^2
What is Z?



With no capillary entry pressure:
Z = 15.3 ft (4.7m)

With capillary entry pressure:
Capillary entry pressure = 0.12 ft of Diesel
Z = 15.0 ft (4.6 m)

Answer to Quiz Question #1: 4.5 m or more!

Vertical Migration of LNAPL
(Hydrodynamic Case)

Mercer and Cohen 1990 – Define minimum vertical hydraulic gradient required to prevent upward LNAPL migration

Solely a function of LNAPL and water Density

Neglecting capillary pressure

For previous example ρ_n = 0.85 g/cc

Minimum vertical gradient that prevents upward LNAPL movement is 0.15 (ρ_n = 0.85 g/cc)

Gradients observed at the sites are below

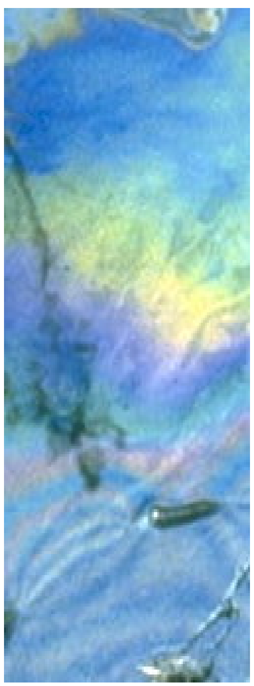


Table 1: Observed Hydraulic Gradients

Site	Stratigraphic Section of Gradient	Vertical Gradient	Horizontal Gradient
Gulf Coast	FGS to underlying permeable unit	0.1	0.002
Midwestern	FGS to base of FGS	0.10 – 0.30	0.08
Southeastern	Within FGS	0.22 – 0.33	0.01
Southeastern	FGS to base of FGS	0.5 – 0.7	0.01
Southeastern	FGS to underlying limestone	0.43 – 0.52	0.01

How far can LNAPL go below the water table

(when restricted to a macropore network)

- Accounts for hydrostatic LNAPL pressure
- Accounts for vertical gradient (J_z)
- Accounts for threshold entry pressure
- If J_z is > 1 - density ratio LNAPL will be carried downward to permeable zone where J_z is diminished
- Example Gasoline specific gravity ~0.88; if J_z > 0.12

$$Z = \frac{\rho_{oil}\left(Z_w + Z_p\right) - \rho_w h_c}{\rho_w(1 - J_z) - \rho_{oil}}$$

Adamski et al. 2005

Table 1: Observed Hydraulic Gradients

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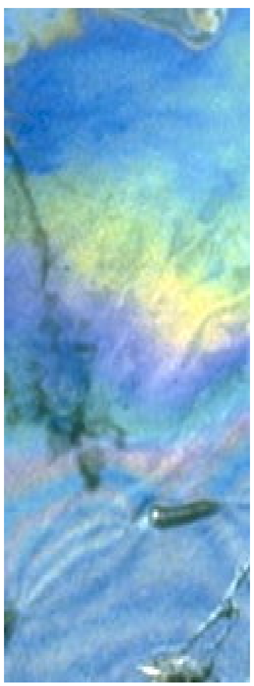
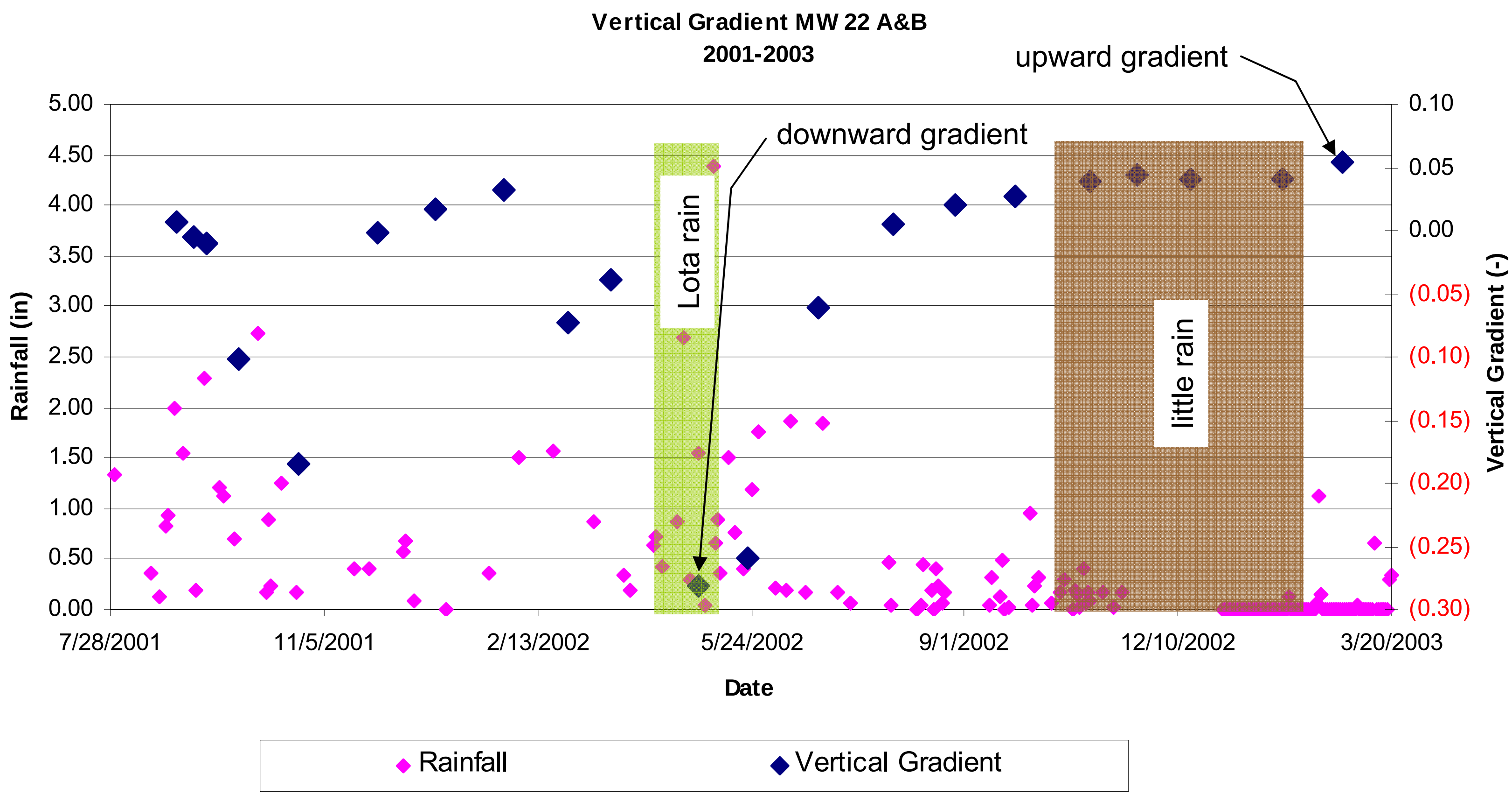


Vertical Gradients Measured at FGS Site ’01 to ‘03



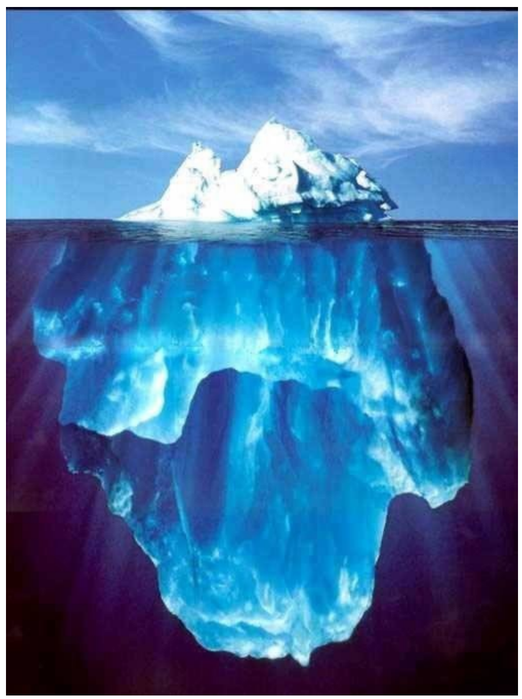
average gradient = (0.03)

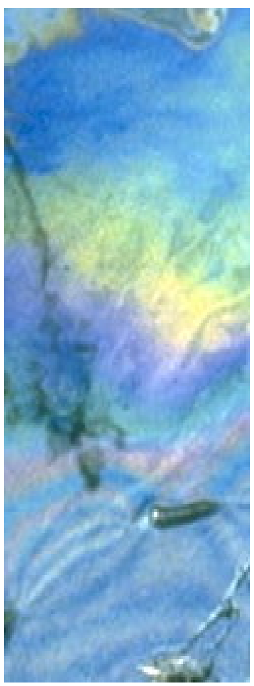
Analogies for Vertical LNAPL Migration FGS

Hydrodynamic Case – It's like an olive oil layer in a beer bong

(Photo obtained off the web
- Jimmy Buffet Concert)

Hydrostatic case – LNAPL is like an iceberg





LNAPL in the subsurface

Observed LNAPL Saturation – The Data

338 LNAPL Dean-Stark saturation analyses (~25cc samples)

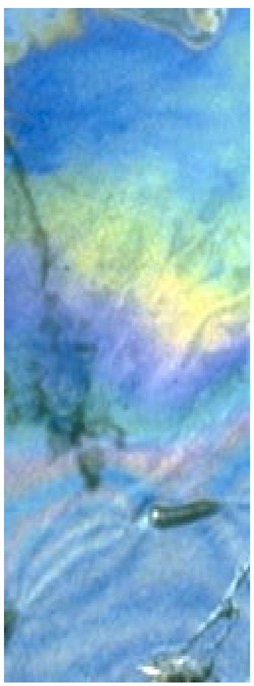
Taken from most heavily LNAPL impacted portions of 11 BP sites

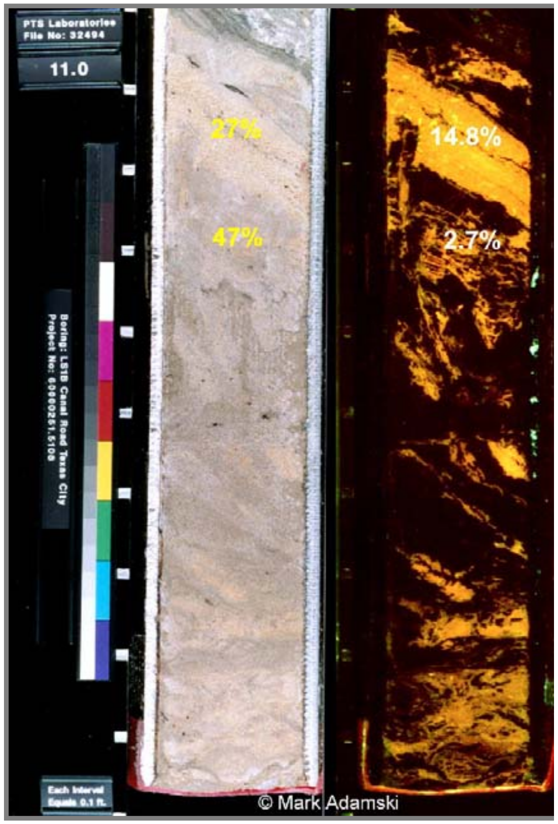
- 7 Refineries
- 2 Chemical Plants
- 1 Bulk Terminal
- 1 Pipeline

LNAPL thickness in observation wells adjacent to sample locations averaged 1.3 m (4.36ft) at 59 locations

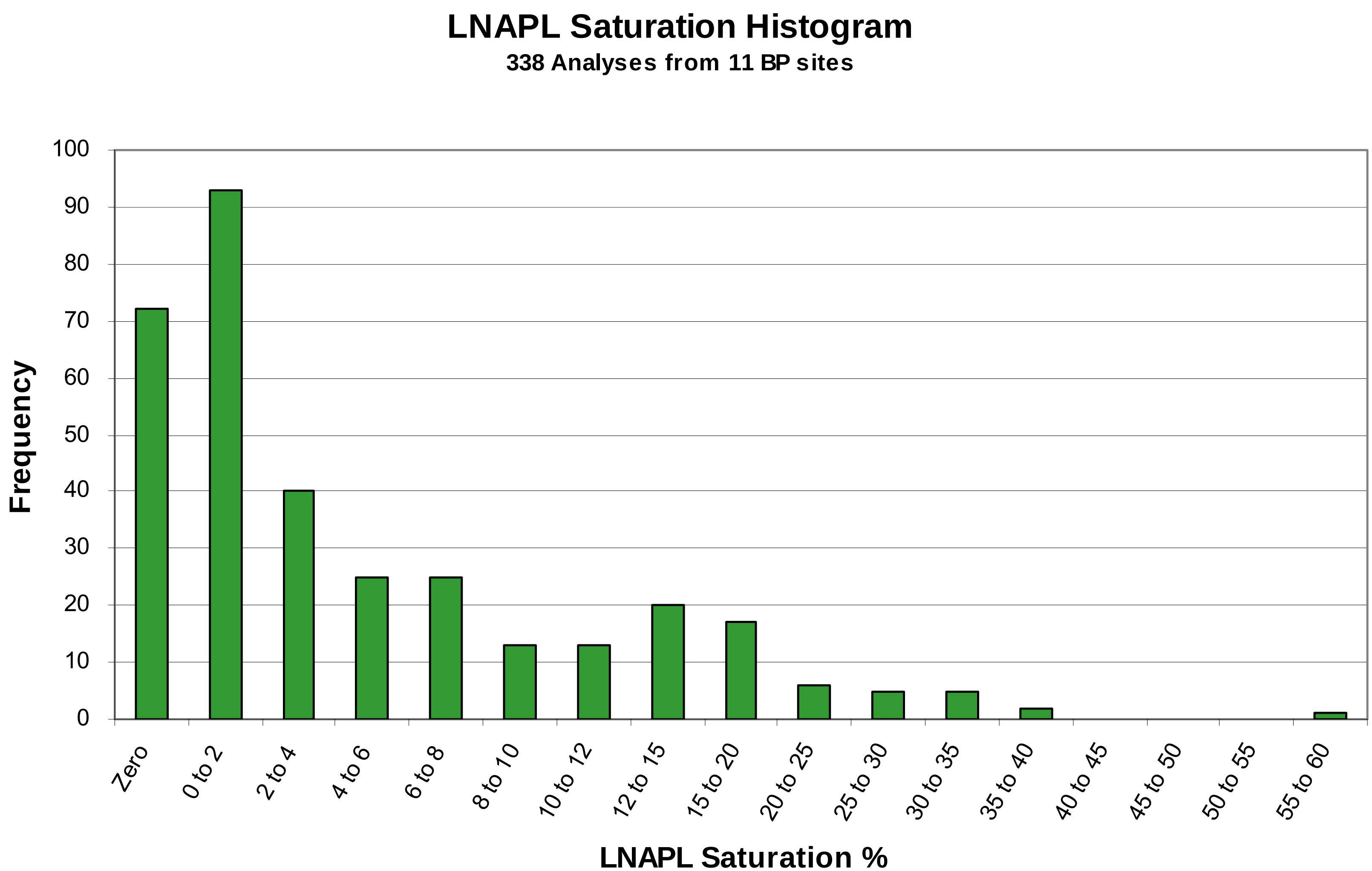
LNAPL Thickness ranged up to 4.66m (15.3 feet)

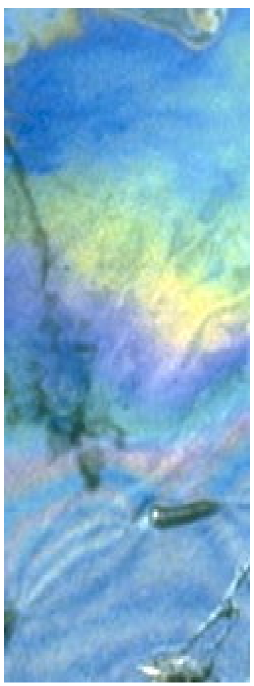
Carefully logged for soil type





LNAPL saturations in place



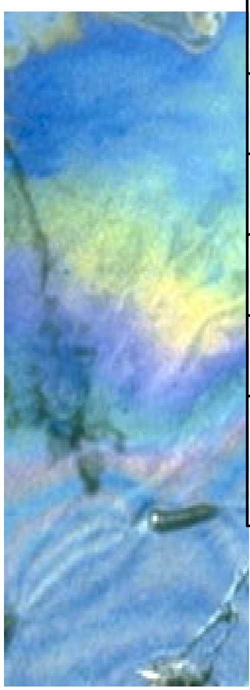


Statistics for all 338 LNAPL saturation analyses

- **Average LNAPL saturation = 5.6%**
- **Median LNAPL saturation = 2.2%**
- **Total # of analyses > 30% = 9**
- **Total # of analyses > 20% = 20**
- **Total # of analyses > 10% = 68**
- **Total # of analyses > 2% = 171**
- **97.34% < 30% saturated**
- **94.08% < 20% saturated**
- **79.88% < 10% saturated**
- **49.41% < 2% saturated**
- **Max Saturation = 56.5% (next highest = 37.3%)**

Saturations by Soil Type

As one would expect – higher saturations in coarse grained soils – all are lower than we would have anticipated.

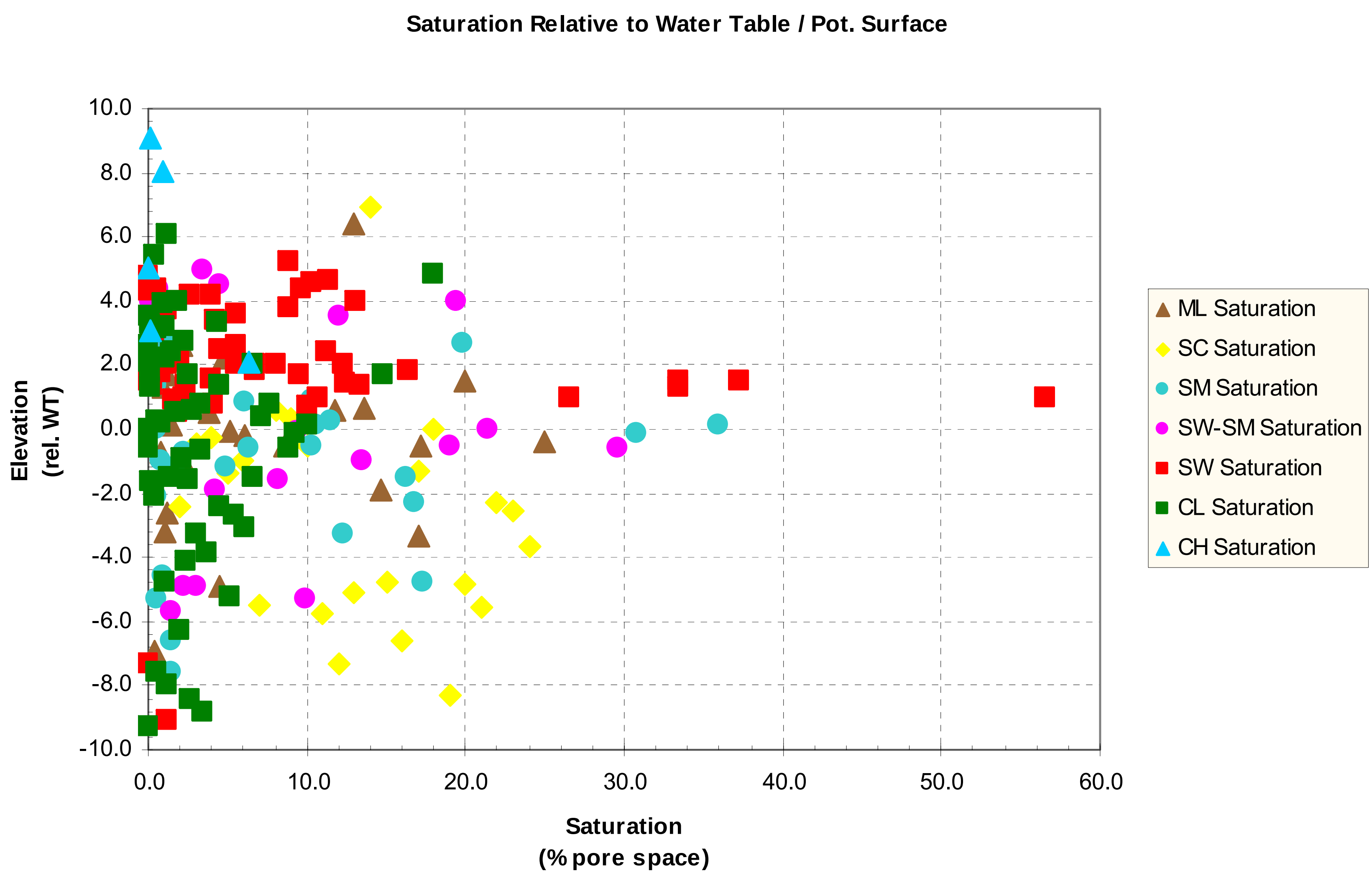


LNAPL Saturation Statistics By Soil Type

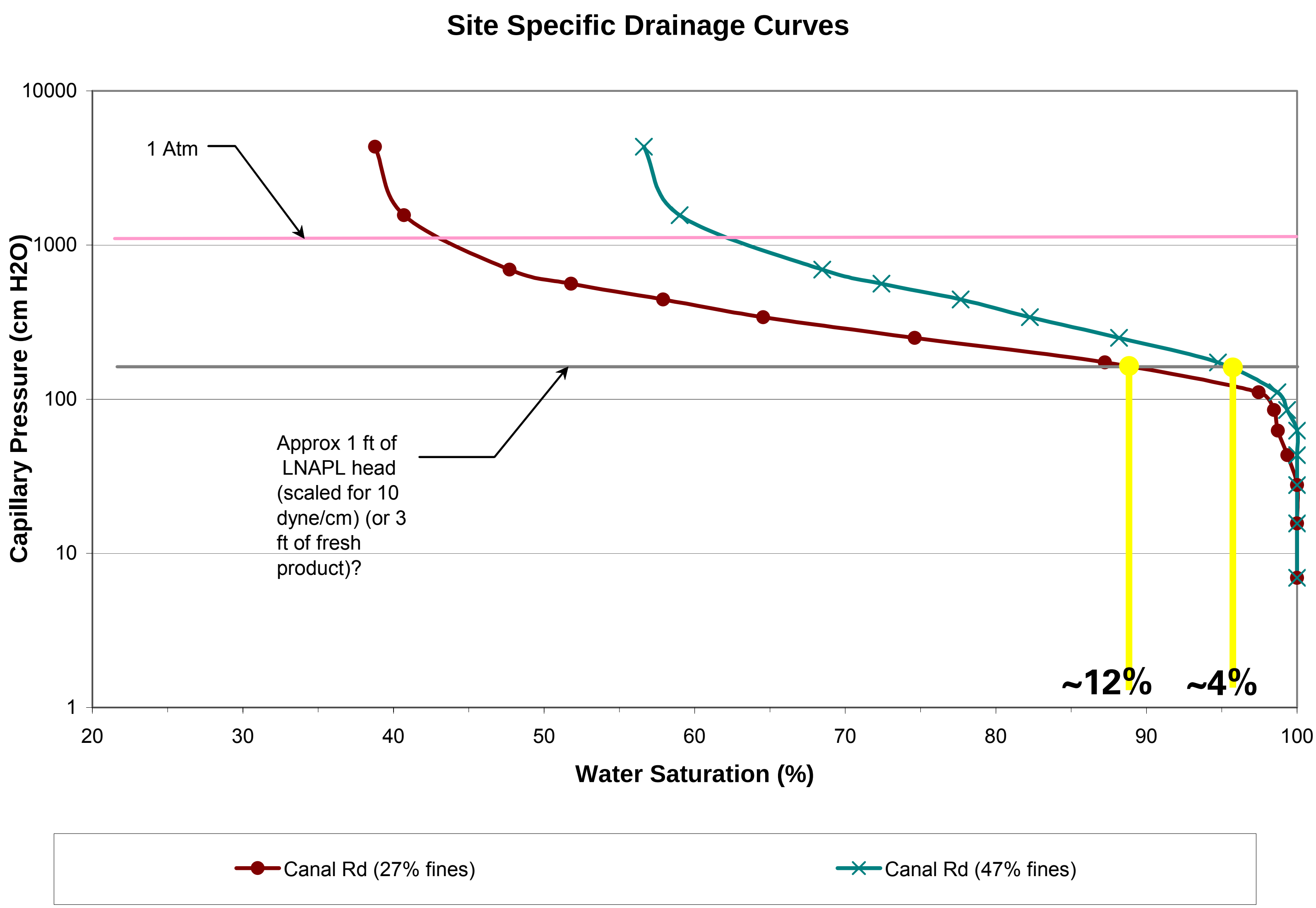
Soil Type	CL	ML	SC	SM	SW-SM	SW
Total # of Samples	84	57	24	55	22	56
Max LNAPL Sat. %	18.0	36.4	20.1	35.9	29.6	56.5
Ave sat. %	2.8	5.8	5.6	5.9	7.4	7.7
Max LNAPL Thickness (obs. in well) (ft)	15.3	13.9	7.5	8.3	8.3	2.4
Ave LNAPL Thickness (obs. in well) (ft)	5.9	5.3	3.7	2.8	5.8	0.8
Number of samples > 20%	0	4	1	4	2	5
Number of samples > 10%	2	13	6	14	6	14
% greater than 20% saturation	0.0%	7.0%	4.2%	7.3%	9.1%	8.9%
% greater than 10% saturation	2.4%	22.8%	25.0%	25.5%	27.3%	25.0%

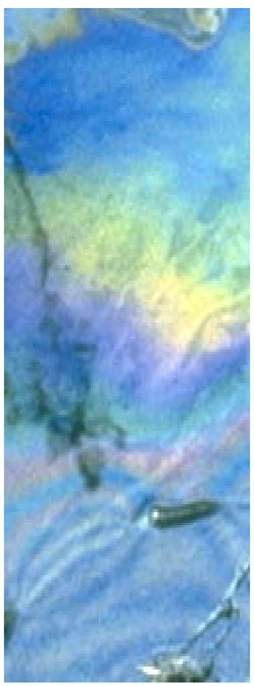
CL = Clay; ML=Silt; SC=Clayey Sand (<50% fines); SM=Silty Sand (<50% fines); SW-SM=well graded sand with silt (5-12%fines); SW=well graded Sand(<5% fines)

Saturations Relative to Water Table

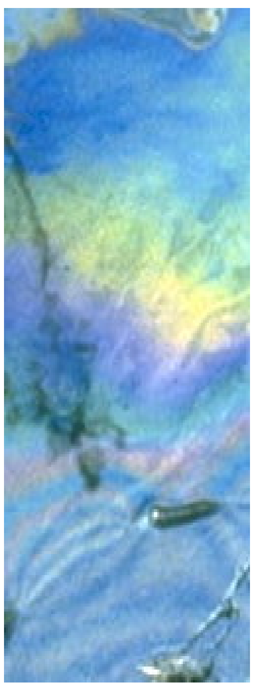


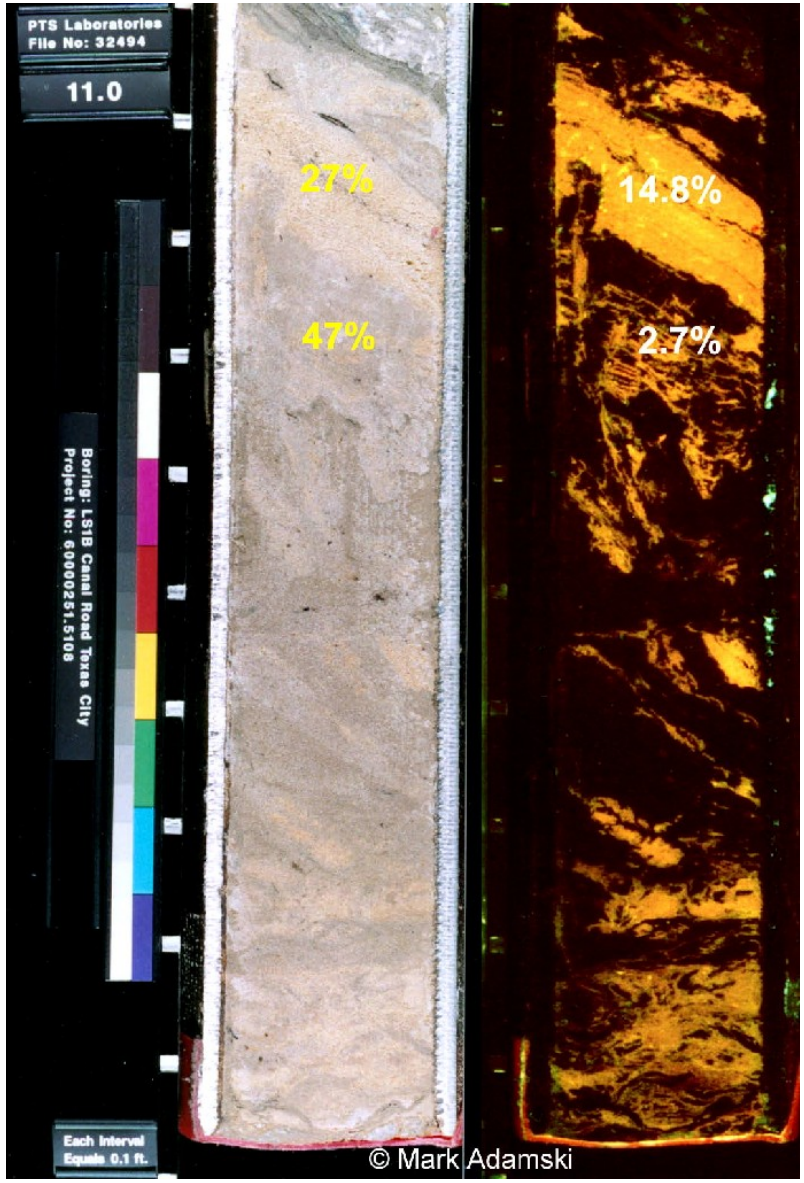
why are saturations low?



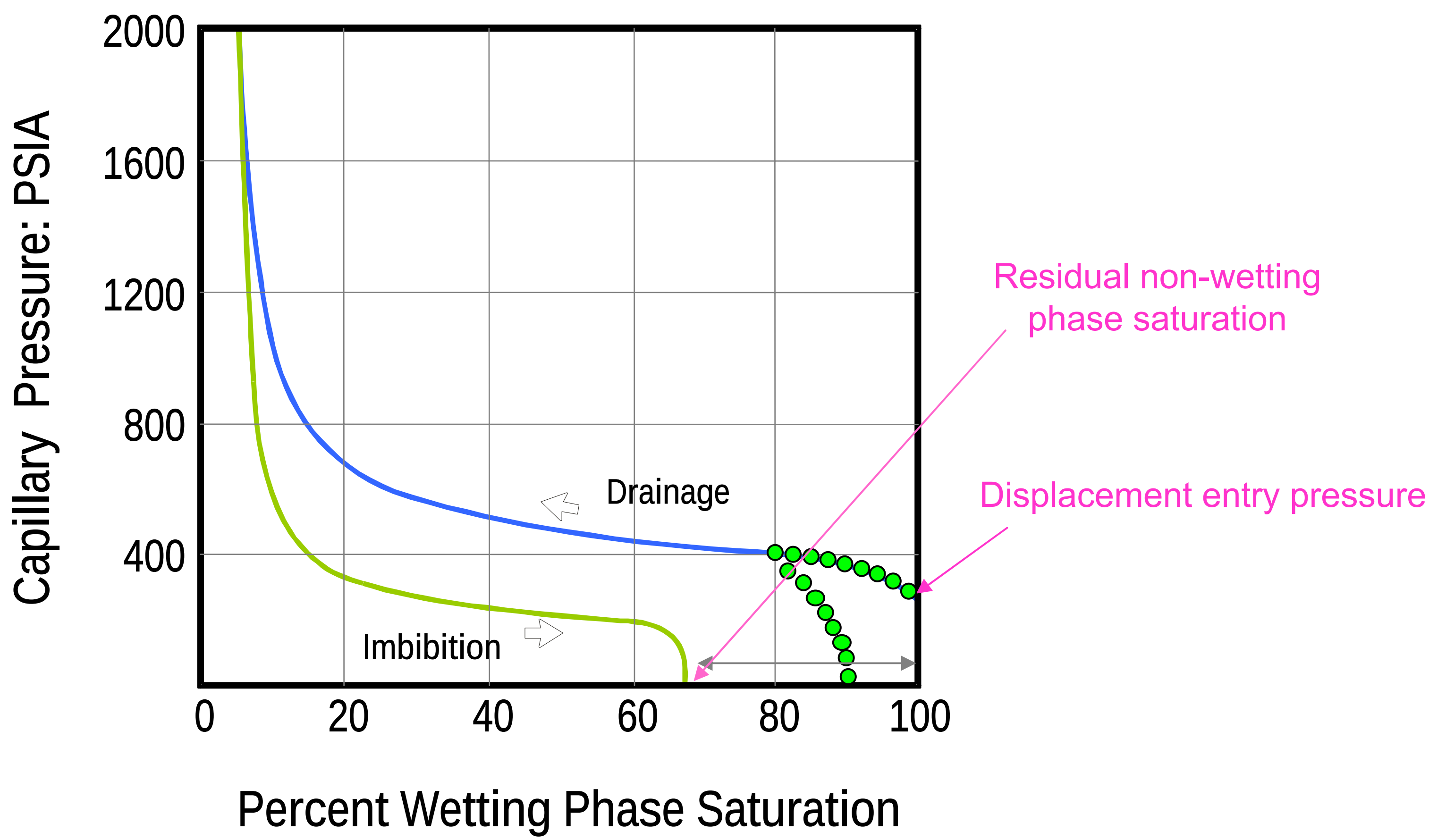


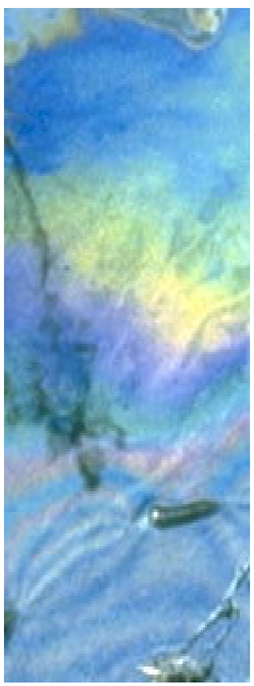
Clayey sand soil w/ fluorescing benzene



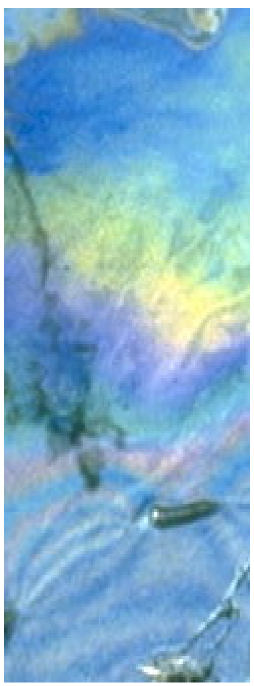


How do low LNAPL saturations impact our view on residual saturation?





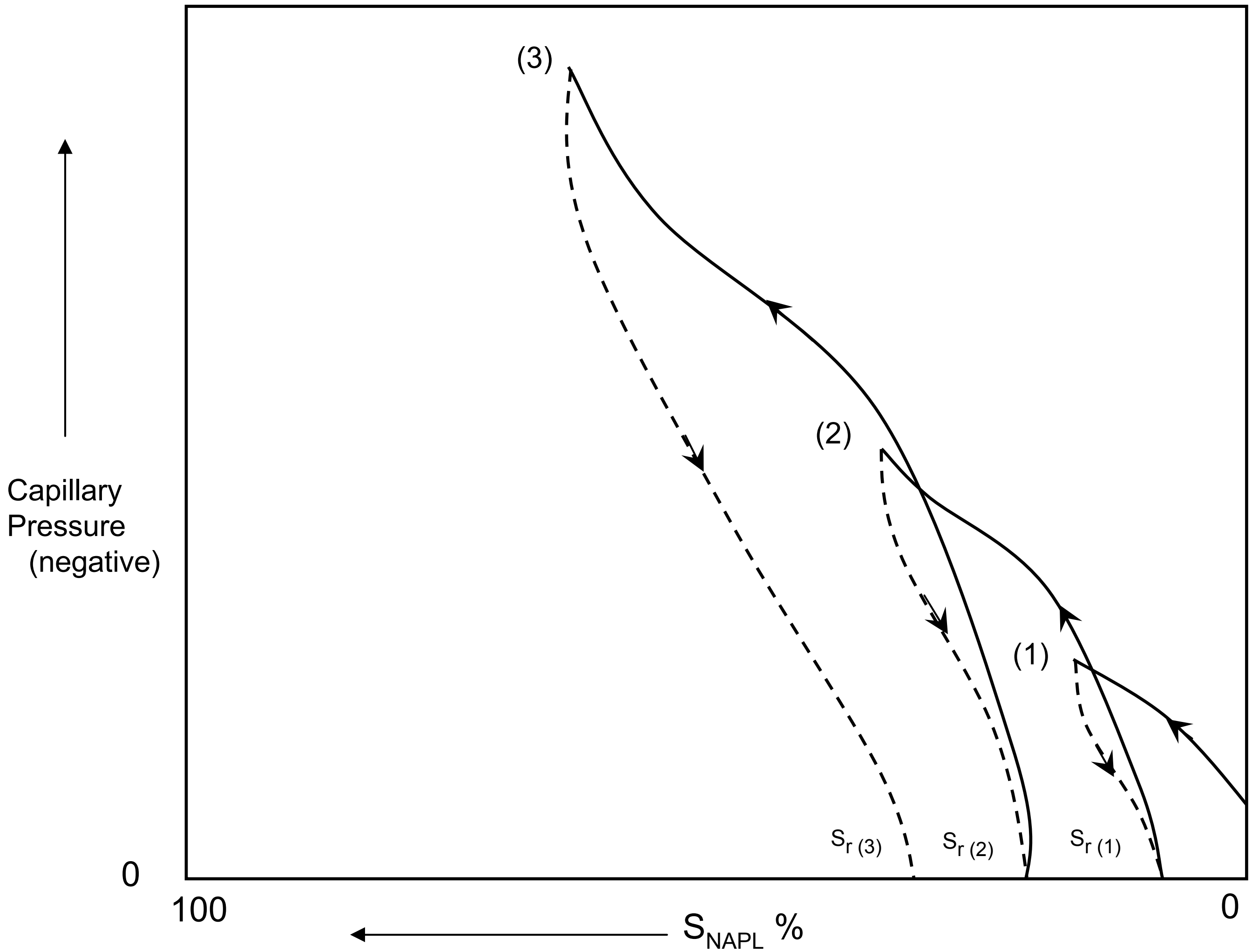
Reality of residual LNAPL saturation



residual saturation:

- is not a fixed parameter based solely on soil type
- it is dependant on both soil type and lnapl pressure (spill) history
- the more lnapl that gets in right after the spill – the higher the residual saturation will be
- remember – our lnapl spills don't develop much pressure (capillary pressure)

Residual f(n) of Initial Saturations

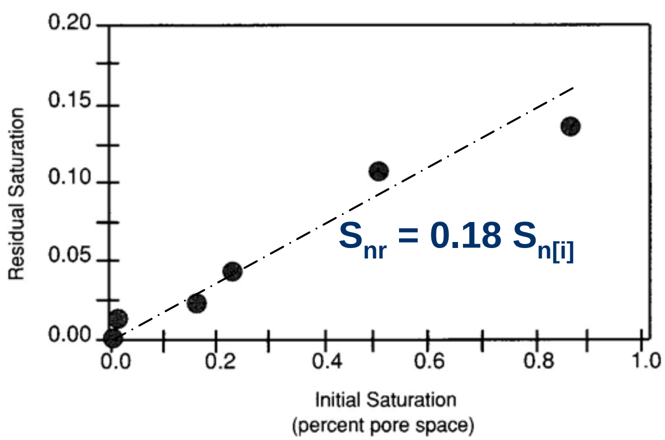


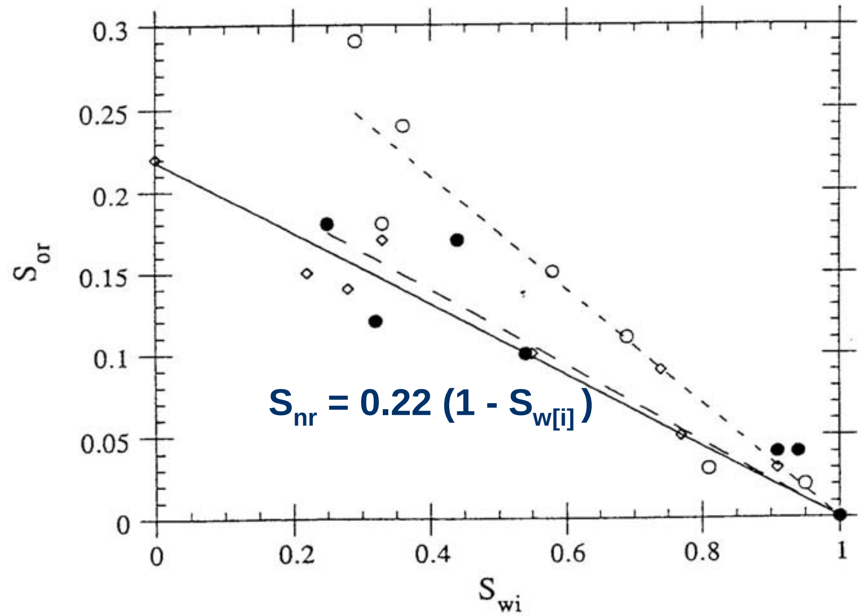
Field and Laboratory Studies of Residual LNAPL Saturation

Model Equation:

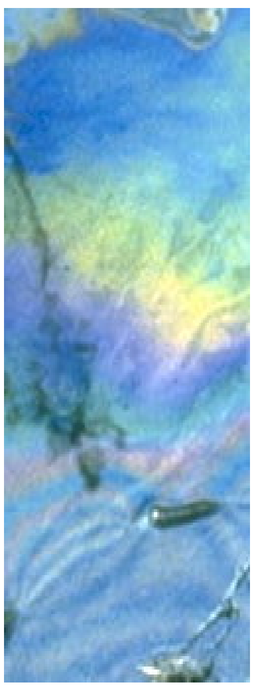
$S_{nr} = f\, S_{n[i]} = f\,(1 - S_{w[i]})$

Kueper et al (1993) – Borden sand

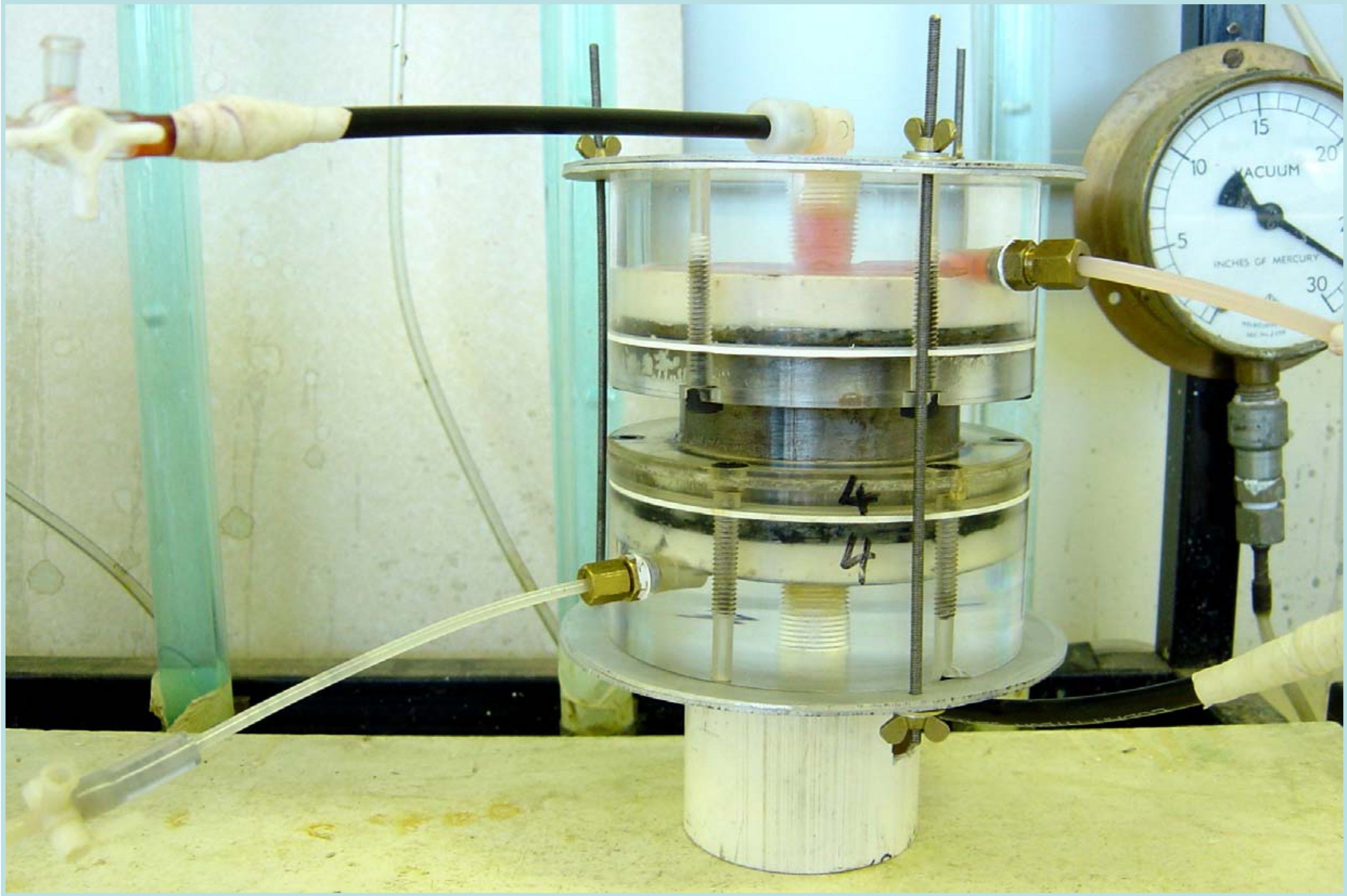




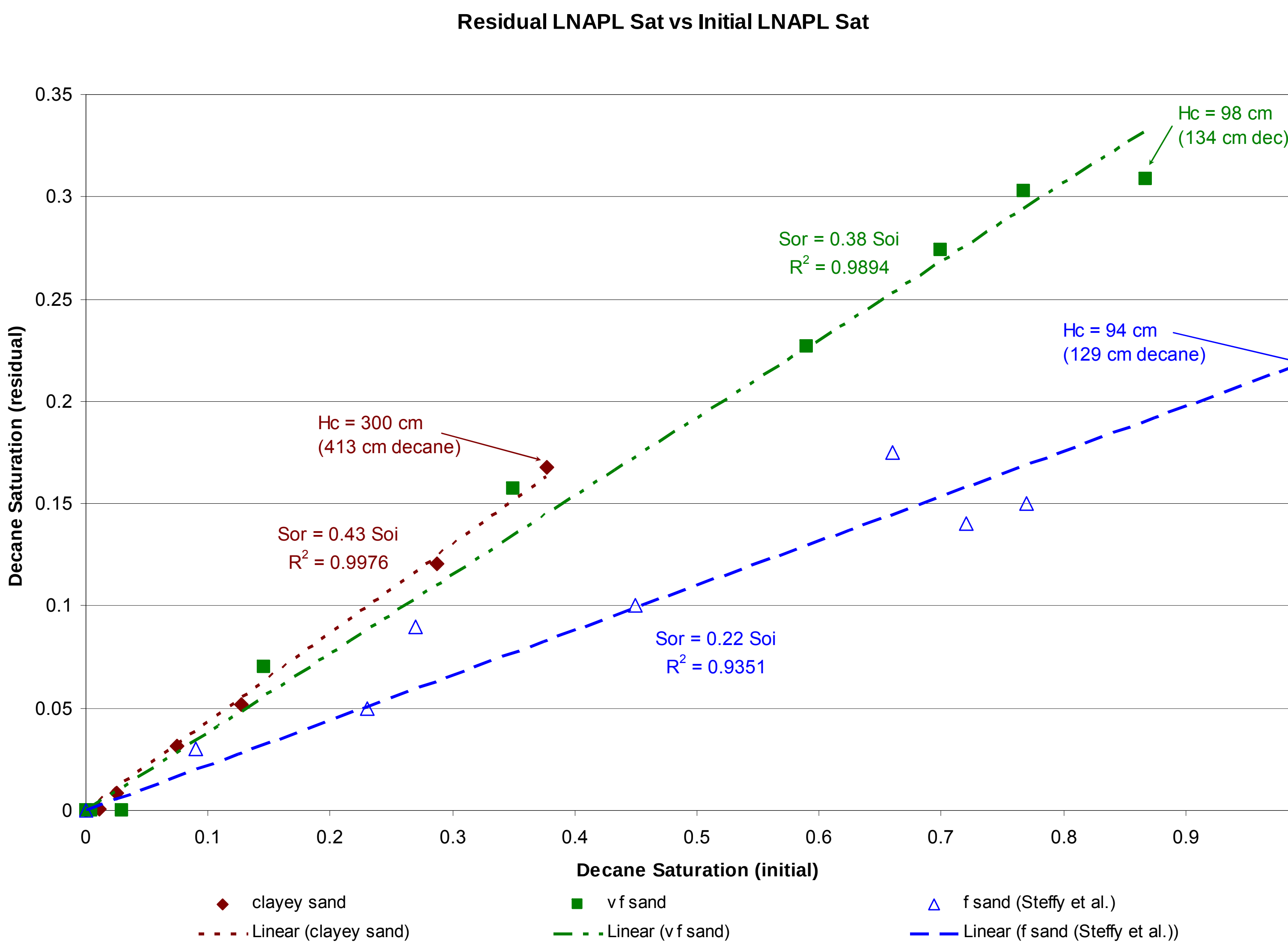
Steffy et al (1997) – fine-medium sand

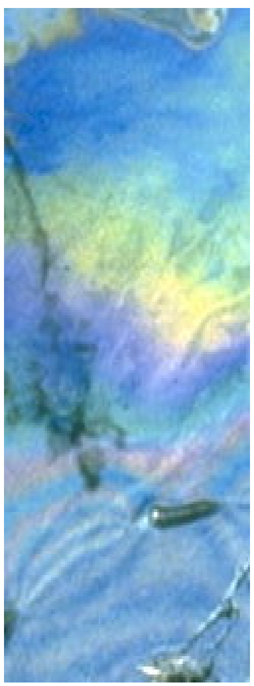


BP / CSIRO Residual project



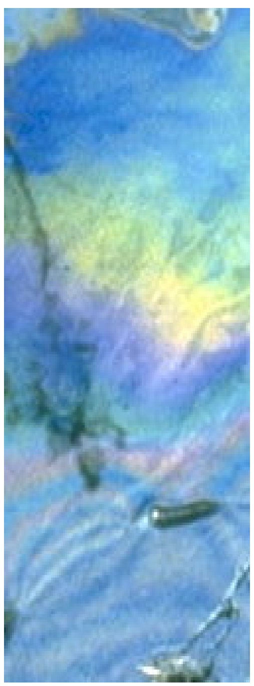
Relationship between initial and residual for three soils





Key Points

- LNAPL fluid pressures in the field are low, as a result LNAPL only enters largest pores (macropores) in FGS
- Being confined to the large pores, LNAPL can penetrate below the water table
- Vertical gradients in FGS can play an important role in LNAPL distribution within the soil profile
- LNAPL being restricted to macropores results in low initial LNAPL saturations
- Low initial LNAPL saturations result in low values for residual LNAPL saturation
- As will be seen in the case studies: a soil that allows 4.7 m of LNAPL to collect in a well contains the equivalent of 2.7cm of LNAPL (formation specific volume)!!



Thank You

LNAPL **in the subsurface**